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Assessment of Downscaling Planetary Boundaries to Semi-Arid Ecosystems with a Local Perception: A Case Study in the Middle Reaches of Heihe River

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Abstract: The middle reaches of Heihe River are located in the oasis of the Gobi Desert where limited freshwater supply supports more than 1.5 million inhabitants. The intense agricultural activities are depleting the groundwater reserve. Consequently, natural landscapes and habitats are degraded. Though such development improves the livelihood of the local community, long-term sustainability of the ecosystem is at risk. Local authorities must be informed holistically to prepare for adapting to the changes and/or mitigating the impacts. The purpose of this study was to perform a regional sustainability assessment based on downscaling the planetary boundaries (PBs). We proposed a regional safe operating space framework that applied a top-down approach using the environmental monitoring data, and a bottom-up approach using knowledge from the local perception about environmental disaster. We conducted on-site samplings and interviews of residents to demonstrate the method. Overall, we showed that the middle reaches had transgressed the safe operating space, particularly on the freshwater use and biogeochemical flow dimensions. We found that the local perception acquired from interviews complemented the insufficiency of the monitoring data and provided the insightful social implications of transgressing the safe operating space, i.e., the anticipated impacts on local livelihood, for policy support.

Keywords: sustainability assessment; semi-arid ecosystem; local perception; planetary boundaries; regional safe operating space; downscaling planetary boundaries; sustainable development

1. Introduction

The Heihe River Basin is an inland river basin, and an oasis in the Gobi Desert, Northwestern China. The enclosed semi-arid ecosystem has minimum rainfall [1]. Freshwater is supplied predominantly by Heihe River, which originates from the snowmelt and glacier melt of the Qilian Mountains. Despite limited water resources, the basin is supporting more than 1.5 million inhabitants. Intensive human activities have been exerting pressure on the natural environment over the past 2000 years [2]. Historically, the basin was a strategic location to defend against nomadic tribes and function as a trading post of the ancient Silk Road. Irrigation systems that divert water from the river have been widely introduced to produce enough food for growth [3]. Consequently, artificial oases with crop plantations have replaced the natural oases [2,4]. In the twentieth century, agricultural activities have shifted to cash crop plantations, especially for water-effective seed corn [5]. However, the expansion of farmlands causes more water stress and induces water conflict [6]. In fact, the desert area has shrunk by 7% from 2011 to 2010 due to conversion to arable lands [7]. Excessive fertilizer application has increased nutrient loading to the water system, while pesticide and herbicide residue has affected the soil health. Dealing with the multi-dimensional pressures, local policymakers must be supported with a holistic assessment of the sustainability of the ecosystem to realize an economic development that simultaneously delivers livelihood improvement without risking ecosystem integrity.

Planetary boundaries (PBs) are a comprehensive evaluation methodology for determining global sustainability [8,9]. PBs categorize anthropogenic impacts into critical ecological processes, i.e., climate change, nutrient flow, freshwater use, ocean acidification, air pollution, ozone depletion, land-use change, biodiversity loss, and human-made chemical pollution. With quantifiable indicators and boundary settings, PBs define the safe operating space as three states: safe, uncertain, and high risk. Although PBs are intended for a global scale assessment [10,11], studies have shown the merits of downscaling PBs to regional ecosystems [10,12,13] as national and provincial governments have great autonomy in policy-making. With a downscaled framework, environmental policy can be tailor-made to reflect the local priorities without neglecting global sustainability. However, not all ecological processes have clear boundaries or thresholds at a regional level. Dearing et al. (2014) [10] proposed defining the safe/high-risk boundaries by first characterizing local ecological processes into four pattern types based on their nature—linear trends, nonlinear trends, thresholds, and early warning signals—and then deciding the state based on the observation of historical data. Nykvist et al. (2013) [13] proposed allocating the allowable emission/effluent usage per capita and other economic factors as alternatives. Cole et al. (2014) [12] used mixed methods based on expert judgment to select the most relevant sets of indicators for South Africa. Although these studies have demonstrated the feasibility of downscaling PBs from a top-down perspective, they notably demand a large number of local datasets. In most cases, there will be a situational compromise between an unavailable ideal indicator (i.e., good resolution and accurate) and an alternative proxy (i.e., low resolution but reasonable), especially for developing countries that have limited monitoring capacity.

This study proposes complementing the top-down approach of downscaling PBs with a bottom-up assessment—using local's perceived risk of environmental disasters—to define a regional safe operating space (RSOS). Environmental psychology studies have shown that the formation of local perception is often associated with living experiences, observed changes in an environment, and other factors varying with particular socio-cultural backgrounds [14–17]. Ecological boundaries in PBs or a RSOS can be viewed as the gradients of increasing risks of environmental disasters [18]. The potential threads on local livelihood show the vulnerability of a community. The vulnerability can be understood as a pre-event state function of the exposure and sensitivity of the system or as a local manifestation of a social response to biophysical risk [19]. For instance, the perception of rural farmers, whose livelihoods depend on the natural environment, possess the valuable tacit knowledge to estimate the health of the local ecosystem [20]. With an appropriate field survey design, local perceptions can be harnessed systematically and thus represent the variation of ecological processes at the small community level. This knowledge provides realistic on-site detail that is often lacking in top-down approaches.

Developing action to prevent environmental disasters requires the integration of biophysical information and understanding of how disasters are perceived by the local communities [21]. Local perception can help policymakers to predict the public responses toward a conservation effort [22]. Lee and Zhang (2005, 2008) [23,24] showed how risk perceptions affect a local community in their behavioral responses of resisting, adapting, accepting, or actively promoting change in a case study. Individuals are particularly sensitive to environmental risks that potentially impact their livelihood [25,26]. As noted by Raworth (2012) [18], an intervention in a regional environment could have an effect on the associated social foundation. The intervention aimed at improving livelihood could in turn impact the environmental boundaries. As such, the dynamics of the environmental boundaries and social foundations are tightly linked. Therefore, the policies for sustainable development need to be appropriately informed and adapted to the practicalities and motivations of regional governance systems to maximize policy influence [10].

2. Materials and Methods

2.1. The Study Area

The study area is the middle reaches of Heihe River (Figure 1). The midstream begins from Yingluoxia to Zhengyixia hydrological stations. The region covers three districts, Zhangye, Linze, and Gaotai, which consist of 91% of the population and 95% of cultivated land and generate more than 80% of GDP in the Heihe River Basin [27]. Therefore, the development in this region plays a critical role in ensuring regional sustainability.

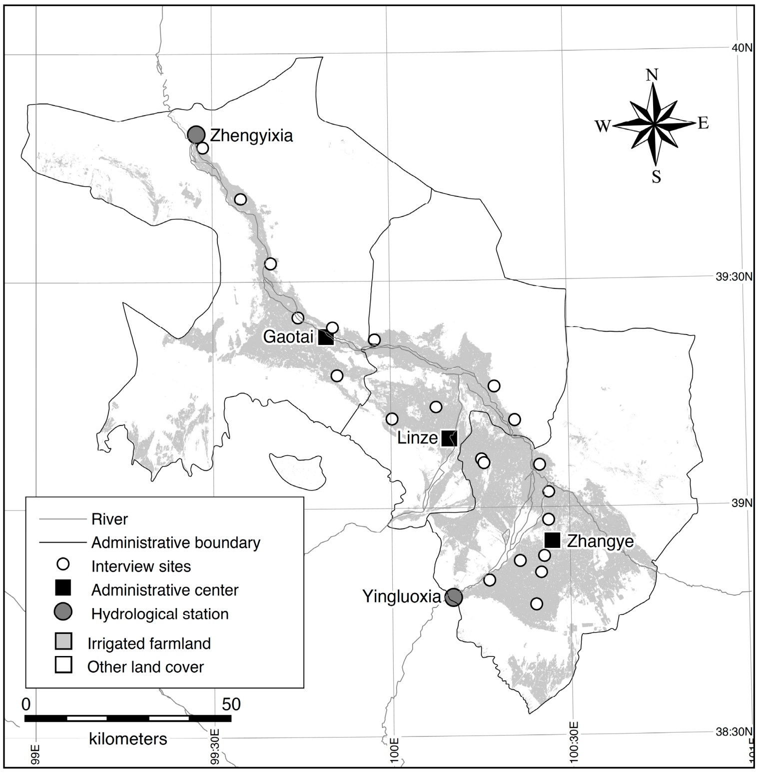

Figure 1. Map of the study area—the middle reaches of Heihe River Basin that begin from Yingluoxia and end at Zhengyixia (gray circles), covering three districts: Zhangye, Linze, and Gaotai. White circles represent the 21 selected interview sites that spread across the irrigated farmland.

This study is designed with two main components: downscaling the PB framework to the local ecosystem or the RSOS in Section 2.2, and complementing the RSOS assessment with local perception and knowledge in Section 2.3.

2.2. Downscaling Planetary Boundaries to a Regional Safe Operating Space

We downscaled PBs to the RSOS with the selection of a series of dimensions and indicators, and a redefinition of boundaries (Figure 2). First, we filtered the ecological dimensions based on the existence of regional thresholds. Then, we examined the representativeness of primary indicators and whether the relevant data was available. If not, we selected an alternative with expert judgment. We quantified the current status based on on-site sampling and secondary data obtained from monitoring stations. Next, we examined whether the boundary definition in PBs applied to the regional level. If not, we redefined the boundary with existing environmental regulations or with the government's goals. Finally, we classified the current status in three tiers, i.e., high-risk, uncertain, and safe, in response to the local ecosystem thresholds. The overview of the decision-making processes of the RSOS framework is shown in the flow chart in Figure 2.

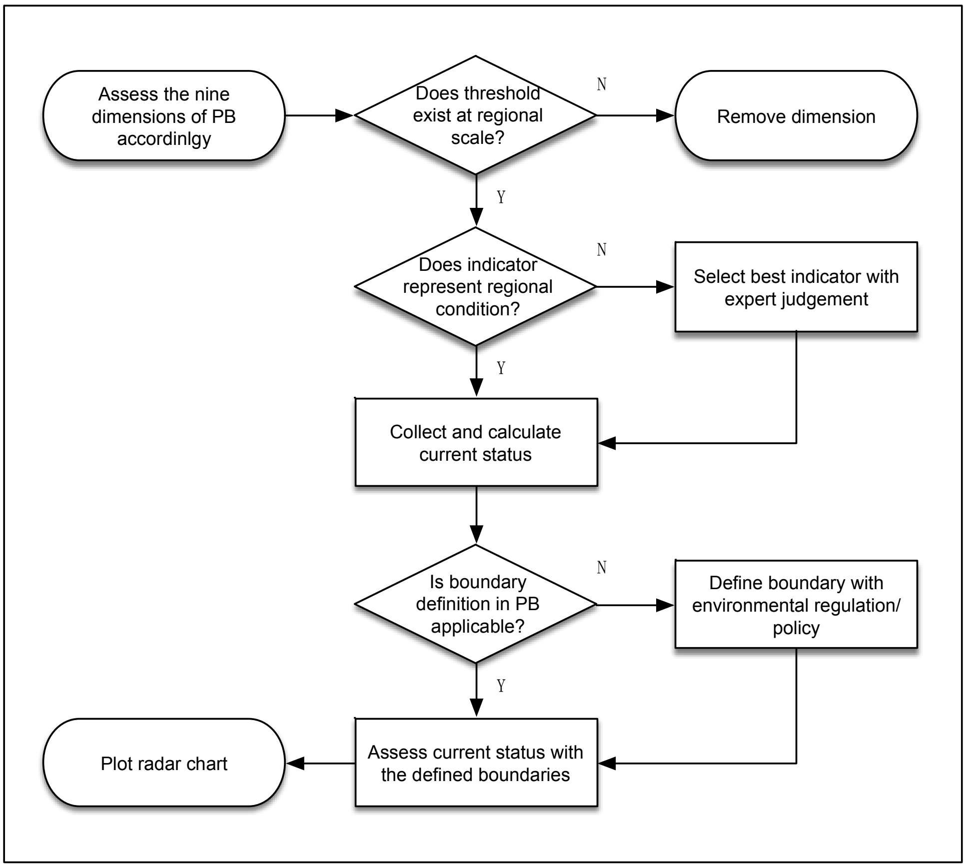

Figure 2. Decision-making flow chart of downscaling the environmental dimensions, indicators, and boundaries from Planetary Boundaries to Regional Safe Operating Space.

2.2.1. Freshwater Use

We defined the high-risk boundary for freshwater use as the level of water consumption exceeding the available water in the basin, and safe as consumption that is 20% less than the freshwater availability. We estimated the total available water was 2.25 to 2.5 billion m^3 annually based on Gansu Water Resource Bulletin [6,28], of which 85% was river water and 15% was groundwater [27]. The water consumption of Zhangye was 2.39 billion m^3 in 2010 and agriculture accounted for 94% of the consumption [29]. The data might be imprecise due to estimation methods. To supplement the assessment, we further sampled the groundwater level in selected villages.

2.2.2. Biogeochemical Flow

We measured the biogeochemical flow using nitrate and phosphate concentrations at the Zhengyixia Hydrological Station, the exit point of the midstream. The nitrate concentration was 1.49 mg/L, and the phosphate concentration was 0.2 mg/L based on the on-site test kit analysis. We used PACKTEST developed by Kyoritsu Chemical Check Lab. We defined the boundaries based on the environmental quality standards for surface water in China [30]. The high-risk boundary was set as 2 mg/L of total-N and 0.4 mg/L of total-P, and the safe boundary was assumed to be half of the limits. Additionally, we sampled selected water wells for the nitrate concentration test to show the vertical distribution of N.

2.2.3. Land-System Change

We measured land system change by using the total coverage area of natural landscapes, i.e., grassland, forest, and wetland. We estimated the total area of natural landscapes was 20.14% based on a remote sensing study [7]. The composition of land use was 6.17% of constructed land, 12.11% of desert, 62.58% of arable land, 4.23% of forest, 10.55% of grassland, and 4.36% of wetland in 2010. We defined the safe boundary as preserving a minimum of 20% of land as natural landscape based on the government's goal stated in the 12th Five-Year Plan.

2.2.4. Atmospheric Aerosol Loading

We measured the air pollution dimension with particulate matter loading, PM_{10} [12]. The PM_{10} level in Zhangye was 36 $\mu g/m^3$ based on local monitoring data. The safe boundary was set at 50 $\mu g/m^3$ (measured in a 24 h average), and the high-risk boundary was set as 150 $\mu g/m^3$ based on Chinese national air quality standards. Although the PM_{10} concentration varies in seasons, the agriculturally based society had limited direct emission. The local air quality was greatly influenced by naturally occurring sandstorms rather than an anthropogenic source.

2.2.5. Novel Entities

We measured novel entities with the usage of pesticides and herbicides for the oasis [31]. We defined the safe boundary as no detectable pesticide and herbicide residue in the harvested crops. The local authority had announced a plan to survey the pesticide and herbicide usage and the treatment of empty bottles. However, neither reliable data of the residual level nor the actual usage amount of chemicals was publicly available at the time.

2.3. Designing Field Survey for the Regional Safe Operating Space

We conducted a field survey, from 6 to 10 August 2015, to interview residents. We surveyed the local perception of environmental risks based on the five dimensions, the implication of transgressing those environmental boundaries. We visited 21 villages along Heihe River. The sites were to cover the whole middle reaches representatively; each site was about 10 km apart. The distribution of interview sites was plotted in Figure 1. We interviewed 2–3 respondents who had been living locally for more than ten years in each village. We administered the interview with the help of two local Chinese students. The duration of each interview was about 15 min. We obtained 58 respondents in total, of which 55% were male, and 45% were female; their highest educational levels were 38% primary school, 36% junior high school, 9% high school, and 17% without formal education; 80% of them were over 40 years old. Most of the respondents were farmers.

The semi-structured interview consisted of four parts. The first and second parts were designed to warm up the respondents and to establish a background context on the changes in the local environment and livelihood. Therefore, they were not included in the assessment. The third and fourth questions are described in Sections 2.3.1 and 2.3.2, respectively. Moreover, a pilot study was conducted in Lanzhou Province before the field survey. We tested and improved the questions to avoid misinterpretations and ambiguities.

2.3.1. Local Perception on Current Environmental Status

Local perception of the likelihood whereby a given environmental system would exceed its safe operating space was elucidated through the calculation of significant *z*-scores at an α level of 0.05 (*z*-scores of values more than, or equal to ± 1.645) [32]. *z*-scores are an indication of how many standard deviations from the mean of an observed perception score is, and functions as a common means of elucidating the significance of social perception on environmental or ecosystem services [33,34]. In this study, the local perception of environmental sustainability was indicated by the perceived risk of the environmental disaster. We interpreted the five ecological dimensions into plain language with each corresponding environmental risk in the local context, e.g., freshwater use as a significant decrease of river water, biogeochemical flow as deterioration of river water quality, and atmospheric aerosol loading as deterioration of air quality. Respondents were asked to rate the likelihood of each environmental disaster as "not possible", "uncertain", or "very possible". The number of responses in each category was then assigned an ascending score (1 for "not possible", 2 for "uncertain", and 3 for "very possible") to quantify the effect of the social perception of the likelihood that a given environmental system would become unsustainable in the near future. This score was then compared against a non-weighted mean, which assumed a respondent distribution by the assumption that every category corresponding to any given environmental system was equally likely to be selected. z-scores were subsequently calculated through the elucidation of the number of standard deviations whereby the observed score was from the non-weighted mean.

2.3.2. Implication of Transgressing Safe Operating Space

We designed an open-ended question to study the implication of the transgressing RSOS. First, we described the five worst-case scenarios that correspond to the ecological dimensions. Then, we asked the respondents to explain how their livelihood might be affected in each scenario. We recorded the interviews and analyzed the content following the principles of grounded theory [35], whereby the perceptions of environmental risks were analyzed without prior hypotheses. We transcribed and identified the keywords mentioned by the respondents and then classified those keywords into five livelihood categories, i.e., getting safe food, access to clean water, earning a sufficient income, maintaining human health, and maintaining a good relationship with neighbors. These categories were selected based on the priority of livelihood shown in a global survey [18].

3. Results

3.1. The Regional Safe Operating Space for the Middle Reaches of Heihe River

The assessment result of the RSOS was summarized in Table 1. Among the ecological dimensions, freshwater use was at the highest risk, as current water consumption of 2.39 m^3/year exceeded the water availability. This was supported by the evidence of observed decreasing groundwater level from 1985 to 2000. The biogeochemical flow was uncertain based on the N and P measurements in surface water; we also found that nitrate had infiltrated some of the groundwater systems. Land-system change and atmospheric aerosols loading were conversely rated as safe. In fact, the arable land had been expanding, while desert had been shrinking in recent decades contributed by the excessive water pumping and water policy that favored agricultural expansion. This novel entity category was defined as an overuse of pesticides and herbicides but was not quantified due to unavailability of the data.

Table 1. Summary of the sustainability status and boundary definition for the regional safe operating space of the middle reaches of Heihe River.

Ecological Dimension	Regional Indicator (Control Variable)	Boundary Definition	Boundary Value (Safe; High Risk)	Current Value
Freshwater use	Water amount (m^3/year)	Water consumption exceeds water availability.	1.80; 2.25	2.39
Biogeochemical flow	Total nitrogen concentration in river (mg/L)	Nutrient concentration exceeds national water quality standards.	1.00; 2.00	1.49
	Total phosphate concentration in river (mg/L)		0.2; 0.4	0.2
Land-system change	Total coverage area of grassland, forest, and wetland (in %)	Natural landscape meets governmental goals.	20; 10	20
Atmospheric aerosol loading	PM_{10} loading (μg/m^3)	PM_{10} pollutant exceeds national air quality standard.	50; 150	36
Novel entities	Pesticide and herbicide residue	Pesticide and herbicide residue meets food standards	-	-

We plotted the result on a radar chart in Figure 3a to communicate the sustainability assessment with policymakers. Although the ecological dimensions were shown in the individual category, their performances were tightly connected by economic activity, i.e., agricultural practices. Two primary solutions had been proposed to mitigate the impact. The first was limiting water use through water policy since water was the main driver for land-system change [1,2,5,36]. This was achieved by allocating a reasonable water quota and introducing additional water costs to the farmers. The second was upgrading the economic activities through industrial transformation [27,28,37]. The government had been promoting a highly value-added industry, as well as a secondary industry (e.g., manufacturing) and a tertiary industry (e.g., service industry). The government had been leveraging the culturally rich ancient sites to promote tourism. As a result, the society has been slowly moving away from intensive agriculture practices, and this could simultaneously mitigate various local ecological pressures.

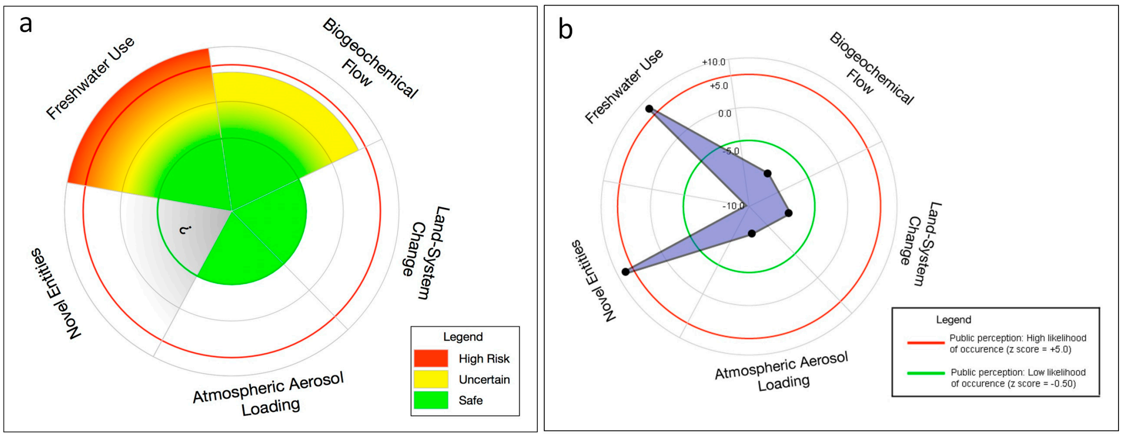

Figure 3. (**a**) Regional safe operating space of the middle reaches of Heihe River based on downscaling planetary boundaries; (**b**) Local's perception on current status based on the likelihood of occurrence of environmental disasters (standardized *z*-scores).

Downscaling the PB framework to the RSOS made it feasible to maintain the original intention and cover critical ecological dimensions in the local ecosystem holistically. However, the approaches for the PBs and RSOS were different. The PB approach was based on model projections that identify thresholds at which significant environmental shifts take place. The RSOS approach was based on regional regulatory standards. Regulatory standards were based on the feasibility of contamination control (technology), economic viability, and social acceptance, as well as the biological response undertaken in toxicological labs using exposure tests on indicator species as surrogates for humans and using data from individual health records.

3.2. Local Perception on Current Environmental Status

Residents of the Heihe River Basin responded to a questionnaire in which they were asked to rank the possibility whereby each environmental component assessed through the downscaling of the planetary boundary would exceed the RSOS. Normalized responses (*z*-scores) corresponding to the social perception of the likelihood of RSOS transgression are summarized in Figure 3b. Significant *z*-scores were classified as perceptions that corresponded to a high likelihood of occurrence (*z*-score > +1.645) or a low likelihood of occurrence (*z*-score > −1.645). Overall, perception trends (Figure 3b) corresponded to clear trends in the RSOS (Figure 3a). Notably, freshwater use was both perceived and estimated to be likely to exceed RSOS boundaries, while atmospheric aerosol loading and land-system changes were similarly perceived and measured to be within safe environmental operating zones.

We compared the differences between the RSOS assessment based on the local perception and the result based on monitoring data in Figure 3a,b. Four out of the five environmental dimensions showed substantial agreement, but not the biogeochemical flow, which locals perceived as safe instead of being uncertain. Two explanations are possible. First, the indicators of nitrate and phosphate concentrations in river water might not have made it possible to distinguish by visual appearance (the visual discernment was only observable when eutrophication happened). Second, fewer lakes and slow flowing water in the middle reaches might have made it difficult to observe local eutrophication. On the other hand, an advantage of the perception survey was highlighted by the novel entity estimation. We were able to overcome the unavailability of monitoring data using the survey results. We could presume that the overuse of pesticide and herbicide had exceeded safety boundaries through the conversation with locals. Subsequently, followed up research should be conducted.

For the responses that disagreed with the majority view in the survey, there are two possible explanations. First, the variation of local perceptions might represent the actual differences of the local environment experienced by the communities, as the survey was conducted in 21 separate villages. Second, it might be a false perception. One example was with respect to natural water abundance: respondents might have perceived the seasonally available water in the irrigation channel, which is managed and allocated by the local authority, as natural river water due to the comprehensive coverage of the irrigation system in the region. Therefore, we could not objectively distinguish the specific water stress area and non-water stress area solely based on the responses.

3.3. Implication of Transgressing Safe Operating Space

We investigated how environmental changes would potentially affect the local community. The results of the local perception survey as a gauge of the impact on local livelihood are summarized in Table 2. More than half of the surveyed residents perceived that all environmental changes would have a negative impact on livelihood if they should exceed RSOS boundaries. About the two ecological dimensions defined as most likely to exceed RSOS boundaries—freshwater use and novel entities—respondents were most concerned that the former would negatively affect their ability to obtain safe vegetables and fruits and to earn a decent income. Eighty-seven percent of the respondents were able to associate the overuse of pesticides and herbicides with a definite negative health impact, while slightly more than half (63%) correlated it with a decline in water quality levels. Although the environmental component of atmospheric aerosol loading was not perceived to exceed safe RSOS boundaries in terms of social perception and biophysical data, it was one of the components evaluated by most of the respondents (91%) to have the most significant potential negative impact on livelihoods, specifically in the health department (92% of respondents). As such, it would be pertinent that this component is closely monitored regarding future environmental impact surveys.

Table 2. Summary of local perception on potential environmental disasters (of each ecological dimension) impact their livelihood, and the breakdown of livelihood impacts based on interview results (the numbers are shown in percentage).

Ecological Dimensions	Having Negative Impact on Livelihood	Breakdown of Livelihood Impacts				
		Getting Safe Vegetable and Fruit	Getting Safe Drinking Water	Earning Enough Income for Living	Maintain Good Health	Maintain a Good Relationship with Neighbors
Freshwater use	0.79	1.00	0.78	1.00	0.18	0.87
Biogeochemical flow	0.72	0.78	0.78	0.78	0.49	0.61
Land-system change	0.51	0.79	0.79	0.69	0.86	0.72
Atmospheric aerosol loading	0.91	0.23	0.25	0.17	0.92	0.19
Novel entities	0.91	0.29	0.63	0.13	0.87	0.13

The local perception approach was different from the ecosystem services approach in understanding the implication of environmental disaster. The former was based on the anticipated social impact caused by ecosystem disruption. The latter assessed services provided by an ecosystem before any disturbance; this was comprehensively reviewed in the Millennium Ecosystem Assessment Report. Therefore, our approach only showed the potential livelihood impact which we assumed to be a significant concern for local government to tailor-make an alternative policy to mitigate the impacts.

3.4. Applicability and Limitation of the Study

We presented the RSOS result to the local government in Zhangye City in August 2015. The officers who attended the discussion included representatives from the environmental protection bureau, the agriculture management bureau, the city planning bureau, and the water research institute. The straightforward and clear representation of the RSOS (Figure 3a) was well received, but there was no plan to adopt the framework in the actual policymaking process at the time. We received feedback and updates on timely ecological concerns. Regarding novel entities, they pointed out a localized problem of excessive plastic mulch use. Farmers used the plastic mulch to reduce evaporation and reduce heat loss due to the cold and arid climate. However, there was no proper disposal of the plastic, causing pollution on the soil. This further illustrated that combining top-down and bottom-up approaches can generate more locally relevant knowledge.

A limitation of this study was the exclusion of environmental dimensions without a local ecological threshold, e.g., climate change. This was not to suggest that they were unimportant in the RSOS. However, we were aimed at exploring the value of local perception on estimating environment status, so only ecological processes with a noticeable impact by the general public have been considered. Alternatively, the survey could be extended to include questions, such as the perception of fair and just consumption, to address those global dimensions [13].

4. Conclusions

In conclusion, this paper proposes a framework that combines top-down and bottom-up approaches to performing a RSOS assessment. We distinguished work from existing studies by highlighting the applicability of the local perception of environmental risks to complement the current ecosystem assessment. We found that local perception was useful as a proxy when monitoring data is lacking. Our results implied that, due to intense human development, the Heihe River Basin had been transgressing its safe operating space, was specifically high risk in freshwater use, and was uncertain in biogeochemical flow and novel entities. We show here that the potential impact on local livelihood was reflected in an on-field survey. The downscaled indicators for sustainability assessment based on PBs could concisely communicate the ecosystem status to local stakeholders about their environmental impact on all dimensions of the ecological boundary.

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